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Abstract: Crop rotation with legumes and conservation tillage systems are advisable practices in rainfed Mediterranean agro-ecosystems, since, in these areas, soils are broadly characterized by low organic matter contents and low fertility. These management practices can substantially modify the dynamics of soil greenhouse gas (GHG) emissions, carbon sequestration and carbon dioxide (CO2) emissions derived from system inputs and farm operations. In this context, a field experiment was conducted under Mediterranean conditions to evaluate the effect of three long-term tillage systems (no tillage (NT), minimum tillage (MT) and conventional tillage (CT)) and two crops (vetch (V, Vicia sativa L.) versus barley (B, Hordeum vulgare L.)) on nitrous oxide (N2O), methane (CH4) and CO2 emissions during one year. Crop yields, soil mineral nitrogen concentrations, dissolved organic carbon and GHG fluxes were measured during the growing season. Soil organic carbon was measured in spring 2012 (18 years after the beginning of a long-term tillage experiment) and together with input and fuel consumption by farm machinery was used to compare the Global Warming Potential (GWP) of the different crop and tillage treatments. Cumulative fluxes of N2O ranged between 0.16 (B-MT) and 0.29 (V-MT) kg N2O-N ha-1 yr-1, resulting in a lower impact on Net GWP than in previous studies. A significant ´tillage x crop` interaction was observed in cumulative N2O emissions (V resulted in higher N2O losses than barley in CT and MT, whereas similar fluxes were observed under NT), which was influenced by soil water-filled pore space, dissolved organic carbon content and denitrification losses, in spite of the presumable predominance of nitrification. Neither tillage nor crop influenced CH4 or CO2 emissions. Yield-scaled N2O emissions (YSNE) were low (< 4 g N2O-N kg aboveground N uptake-1) and significantly higher in B than in V. The most sustainable crop and tillage treatments in terms of GWP were non-fertilized-V and NT, due to higher carbon sequestration and lower fuel consumption under NT and the absence of

mineral N fertilizers in V. These crop and tillage treatments could be considered good management strategies in rainfed Mediterranean agro-ecosystems since they provide the best balance between soil emissions, YSNE and Net GWP.

Highlights

Three tillage treatments (NT, MT, CT) and two crops (vetch versus barley) were evaluated.

GHG emissions, crop yields, yield-scaled N_2O emissions and GWP were assessed.

The interaction of tillage with crop residues from previous crops may have driven N_2O losses.

Vetch resulted in higher N_2O losses than barley in CT and MT, whereas similar fluxes were observed under NT.

NT and vetch had the lowest Net-GWP of the tillage and crop factors, respectively.

Effect of tillage and crop (cereal versus legume) on greenhouse gas emissions and Global Warming Potential in a non-irrigated Mediterranean field.

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Abstract

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on Net GWP than in previous studies. A significant ´tillage x crop` interaction was observed in cumulative N_2O emissions (V resulted in higher N_2O losses than barley in CT and MT, whereas similar fluxes were observed under NT), which was influenced by soil water-filled pore space, dissolved organic carbon content and denitrification losses, in spite of the presumable predominance of nitrification. Neither tillage nor crop influenced CH_4 or CO_2 emissions. Yield-scaled N_2O emissions (YSNE) were low (< 4 g N_2O-N kg aboveground N uptake^{-1}) and significantly higher in B than in V. The most sustainable crop and tillage treatments in terms of GWP were non-fertilized-V and NT, due to higher carbon sequestration and lower fuel consumption under NT and the absence of mineral N fertilizers in V. These crop and tillage treatments could be considered good management strategies in rainfed Mediterranean agro-ecosystems since they provide the best balance between soil emissions, YSNE and Net GWP.

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1. Introduction

Agricultural practices, such as nitrogen (N) fertilization, account for 60 % of nitrous oxide (N_2O) anthropogenic emissions. Nitrous oxide is a greenhouse gas (GHG) whose Global Warming Potential (GWP, 100-year time horizon) is 265 times higher (without inclusion of climate-carbon feedbacks) than that of carbon dioxide (CO_2) (Myhre *et al*., 2013). Agriculture is also responsible for other GHG emissions, such as methane (CH_4) and CO_2. In this context, Rees *et al*., (2013) considered that potential strategies for mitigating total emissions in each cropping system could be developed by making changes in the variables that influence the biochemical processes that trigger GHG emissions from soils, as a result of agricultural operations (e.g. fertilization, tillage, and crop rotation).

Semiarid and arid regions, which represent more than a third of global land, are widely used for rainfed grain crops (Harrison and Pearce, 2000). In these areas, the adoption of conservation agricultural systems including cereal-legume rotations is being promoted and continues to increase each year (Kassam *et al.*, 2010). This is likely due to the improvements in soil physicochemical properties and ecology, as well as economic benefits, that have been associated to these practices (Masri and Ryan, 2006; Roger-Estrade *et al*., 2010; Kassam *et al*., 2012). Moreover, with the new EU mandatory policy, forage legumes are liable to receive the greening payment due to crop diversification and as surfaces of ecological interest (since they are N fixing crops), and also payments associated to crop production. In Spain, which is the leading country in terms of adoption of no-till in Europe (Kassam *et al.*, 2010), the surface area of cereal-forage vetch rotation has doubled in the last four years (MAGRAMA, 2013).

Legume crops have been reported as a N_2O mitigation strategy in many studies (Jensen *et al*., 2012) since no synthetic N is added to the soil. However, grain legumes can produce N_2O emissions, mainly through N release from root exudates during the growing season and from decomposition of crop residues after harvest (Rochette and Janzen, 2005; Wichern *et al*., 2008; Tellez-Rio *et al*., 2015). Management practices, such as soil incorporation of legume residues, and environmental/soil conditions have a great influence on N_2O fluxes derived from legumes. Previous studies have, therefore, reported a high variability in N_2O fluxes (0.03–7.09 kg N_2O–N ha^{-1} yr^{-1}) (Jensen *et al.* 2012). Most previous studies comparing cereal and legume crops have used maize as the cereal (characterized by high water availability and N input during the cereal growing season) (Drury *et al*., 2008; Omonode *et al.*, 2011; Dendooven *et al.*, 2012) or have compared cereals and legumes as catch crops during the intercrop period (Sanz-Cobena *et al.*, 2014a, Bayer *et al.*, 2015). Little is known about rainfed legume-winter cereal annual rotations in semi-arid areas, in comparison with cereal monoculture. Moreover, questions including whether legumes mitigate more N_2O emissions than cereals remain unanswered.

Controversy exists about the effect of tillage on GHG emissions from soils. Either abatement (Six *et al.*, 2004, Dendooven *et al*., 2012) or enhancement (Baggs *et al*., 2003; Beare *et al*., 2009) of N_2O fluxes have been reported following the adoption of conservation tillage. The meta-analysis of 41 studies carried out by van Kessel *et al*. (2013) showed that results are highly dependent on experimental duration, climatic conditions, crop residue composition and management, and N fertilization placement. However, the studies included in this meta-analysis did not consider the interaction effect between tillage and crop. Therefore, further research is needed to gain insight into

the ‘tillage x crop’ interaction and its effect on N_2O emissions, as well as into the response of CH_4 and CO_2 emissions to tillage.

Moreover, an adequate assessment of the effects of conservation tillage practices and crop effect (cereal *versus* legume) on GHG balance requires both site-specific emission data and data on the emissions from inputs production, farm operations (Barton *et al*., 2013) and carbon (C) sequestration. The adoption of NT can increase C stocks in the surface soil layer (Puget and Lal, 2005; Álvaro-Fuentes *et al*., 2014), although some authors have reported that greater soil organic C (SOC) content is accumulated near the bottom of the plow layer in tilled soils (Angers and Eriksen-Hamel, 2008). The best way to assess whether the adoption of NT can effectively increase C sequestration and its relative contribution to the Global Warming Potential (GWP) is through long-term experiments.

The main objective of this study was to evaluate the effect of three tillage treatments (conventional tillage (CT), minimum tillage (MT), and no tillage (NT)), two different crops (vetch preceded by wheat; and barley preceded by vetch) and the interaction of both factors on GHG (N_2O, CH_4, CO_2) emissions, yield-scaled N_2O emissions (YSNE) and GWP. We hypothesized that: 1) N_2O emissions would be lower in NT plots than in CT plots, due to climate conditions and experimental duration (van Kessel *et al.*, 2013), 2) N_2O emissions would be lower in the legume (vetch, V) than in the cereal crop (barley, B), due to the application of mineral N fertilizer in B combined with the effect of V residues, which had a lower C:N than that of the wheat residues that was left/incorporated before the V cropping phase and 3) The replacement of continuous cropping of cereal by cereal-legume rotation with NT management would be an advisable practice to ensure farm sustainability due to the lower labor use in NT and lack of N fertilizer application in V, which lead to an abatement of CO_2 equivalents.

2. Materials and methods

2.1. Site characteristics

The field experiment was carried out at "La Canaleja" Station (40º 32´N, 3º 20´W, 600 m.a.s.l.), in Alcalá de Henares (Madrid, Spain), where a long-term tillage experiment was established in 1994. Since then, several crop (cereal-legume-fallow) rotations have been cultivated (Martín-Lammerding *et al.* 2011). From 2005, the annual crop rotation has been fallow-wheat (*Triticum aestivum* L. var. Marius)-vetch (*Vicia sativa* L. var. Senda)-barley (*Hordeum vulgare* L. var. Kika), for each tillage system (NT, MT, CT).

The soil was a sandy-loam *Calcic Haploxeralf* (Soil Survey Staff, 2010). The main physicochemical properties of the top soil layer (0-15 cm) were: sand, 50.8 %; silt, 37.7%; clay, 11.5%; $CaCO_3$, 41.6 g kg^{-1}; pH_{H2O}, 7.9 and EC, 121.3 µS cm^{-1}. The site has a semiarid Mediterranean climate with dry summers. Mean annual temperature and rainfall from 1994-2013 for this area were 13.5 ºC and 402.7 mm, respectively.

Hourly rainfall and air temperature data were obtained from a meteorological station located at the field site. Soil temperature was measured in each tillage system by inserting a temperature probe 15 cm into the soil. Mean hourly temperature data were stored on a data logger.

2.2. Experimental design and management

This experiment was conducted from October 2012 to October 2013 under rainfed conditions. The experimental design consisted of a *split-plot*, divided into three main plots corresponding to the tillage systems -NT, MT and CT- in a randomized complete three-block design. Each plot was further divided into five sub-plots (10 m x

25 m), assigned in completely randomized design to all phases of crop rotation involving fallow-wheat-vetch-barley and wheat in monoculture. Here, only V and B subplots were studied giving eighteen subplots (3 plots x 2 subplots x 3 replicates -blocks-).

Ploughing was conducted in the first week of October with a moldboard (20 cm depth) in CT plots, and with a chisel plough (15 cm depth) in MT plots. Then, a cultivator pass was carried out in late October 2012 for both tillage treatments. Thus, crop residues (which were left on the ground during summer in all tillage treatments) were almost completely incorporated into the soil in CT, whereas approximately 30% of the surface of MT was covered with the previous season's crop residues. No tillage involved direct drilling and spraying with glyphosate (at a rate of 2 L ha^{-1} of Sting Monsanto ®) for weed control, and the previous season's crop residues were retained on the soil surface. Vetch was seeded on 29th November 2012 with 120 kg seed ha^{-1}, while B was seeded on 14th November 2012 with 210 kg seed ha^{-1}. Mineral fertilization and a post-emergence herbicide treatment were only applied to B subplots. Nitrogen was applied at seeding (16 kg N ha^{-1} as NPK, 8-24-8) and again on 8th March 2013 (54 kg N ha^{-1}as NH_4NO_3, 27-0-0). A post-emergence herbicide treatment was applied in mid-February 2013 using Herbimur Doble® at a rate of 1.6 L ha^{-1}. Insecticide or fungicide applications were not necessary in any of the experimental plots. Vetch and B were harvested on 12th May 2013 and 18th June 2013, respectively.

2.3. Sampling and analysis of GHG emissions

Fluxes of N_2O, CH_4 and CO_2 were measured from October 2012 to October 2013 using the closed chamber technique with opaque manual chambers. One chamber (diameter 35.6 cm, height 19.3 cm, volume 19.1 L) was placed in each subplot.

Chambers were hermetically closed (for 1 h) by fitting them into stainless steel rings inserted in the soil at a depth of 5 cm at the beginning of the study to minimize lateral diffusion of gases and avoid soil disturbance associated with the insertion of chambers in the soil. Rings were only removed during management practices. Each chamber had a rubber sealing tape to guarantee an airtight seal between the chamber and the ring. A rubber stopper with a 3-way stopcock was placed in the wall of each chamber to take gas samples. Greenhouse gas measurements were always taken with B/V plants inside the chamber. When plants exceeded the chamber height (19.3 cm), plastic intersections of 19 cm were used between the ring and the chamber.

Gas samples were taken twice per week during the first month after fertilization events or during rainfall periods, and then, every week or every two weeks until the end of the crop period. After harvest, one sample was taken each month. All samples were taken at the same time of day (10–12 am) to minimize any effects of diurnal variation in emissions.

Measurements of N_2O, CO_2 and CH_4 emissions were taken at 0, 30 and 60 min to test the linearity of gas accumulation in each chamber. Gas samples (100 mL) were removed from the headspace of each chamber using a syringe and transferred to 20 mL gas vials sealed with a gas-tight neoprene septum. Vials were previously flushed in the field using 80 mL of the gas sample. Samples were analyzed by gas chromatography using a HP-6890 gas chromatograph equipped with a headspace autoanalyzer (HT3) from Agilent Technologies (Barcelona, Spain). HP Plot-Q capillary columns transported gas samples to a ^{63}Ni electron-capture detector (Micro-ECD) to analyze N_2O concentrations and to a flame ionization detector (FID) connected to a methanizer to measure CH_4 and CO_2 (previously reduced to CH_4). The temperatures of the injector, oven and detector were 50ºC, 50ºC and 350ºC, respectively. The accuracy of the gas

chromatographic data was 1% or better. Two gas standards comprising a mixture of gases (high standard with 1500 ± 7.50 ppm CO_2, 10 ± 0.25 ppm CH_4 and 2 ± 0.05 ppm N_2O and low standard with 200 ± 1.00 ppm CO_2, 2 ± 0.10 ppm CH_4 and 200 ± 6.00 ppb N_2O) were provided by Carburos Metálicos S.A. and Air Products SA/NV, respectively, and used to determine a standard curve for each gas.

The increases in GHG concentrations within the chamber headspace were generally linear (R^2> 0.90) during the sampling period (1h). Therefore, emission rates of fluxes were estimated as the slope of the linear regression between concentration and time (after corrections for temperature) and from the ratio between chamber volume and soil surface area (MacKenzie *et al*., 1998). Cumulative N_2O-N, CH_4-C and CO_2-C, emissions per plot during the sampling period were estimated by linear interpolations between sampling dates, multiplying the mean flux of two successive determinations by the length of the period between sampling and adding that amount to the previous cumulative total (Sanz-Cobena *et al.*, 2014a).

2.4. Soil and grain sampling and analyses

In May 2012, composite soil samples were collected from each subplot at depths of 0 to 7.5 cm, 7.5 to 15 cm and 15 to 30 cm. Soil samples were air-dried and sieved. Soil organic C was then determined using the wet oxidation method (Walkey-Black). In addition, bulk density was determined using intact core samplers as described in Grossman and Reinsch (2002).

In order to relate gas emissions to soil properties, soil samples were collected from the 0-15 cm depth during the growing season on almost all gas-sampling occasions, particularly after each fertilization event. Three soil cores (2.5 cm diameter and 15 cm length) were randomly sampled close to the ring in each subplot, and then

mixed and homogenized in the laboratory. Soil dissolved organic C (DOC) was determined by extracting 8 g of homogeneously mixed soil with 50 mL of deionized water. Afterwards, DOC content was analyzed with a total organic C analyser (multi N/C 3100 Analityk Jena) with an IR detector. Soil ammonium (NH_4^+-N) and nitrate (NO_3^--N) concentrations were analyzed using 8 g of homogeneously mixed soil extracted with 50 mL of KCl (1 M), and measured by automated colorimetric determination using a flow injection analyzer (FIAS 400 Perkin Elmer) with a UV-V spectrophotometer detector. The water-filled pore space (WFPS) was calculated by dividing the volumetric water content by total soil porosity. Total soil porosity was calculated according to the relationship: soil porosity = (1- soil bulk density/2.65), assuming a particle density of 2.65 g cm^{-3} (Danielson *et al.*, 1986). As in Gómez-Paccard *et al.* (2015), we only measured bulk density once a year (before the start of the experiment, as indicated above), considering that although bulk density diminishes in the topsoil layer immediately after tillage, this effect is short-lived and is followed by a rapid reorganization of the soil. Gravimetric water content was determined by drying soil samples at 105 °C in a MA30 Sartorius ® oven.

Grain yield and above-ground biomass were measured by harvesting two randomly selected 0.5 x 0.5 m squares from each subplot. After sampling V, the rest of the plots were trimmed (regardless of the tillage system), so that V residues were chopped and left on the surface. Aerial biomass was cut by hand at the soil level and weighed after separating weed and crop biomass. Grain and straw were also separated in the case of B. Total C and N content of cereal (grain and straw) and vetch biomass were determined with an elemental analyzer (TruMac CN Leco).

2.5. Yield-scaled N_2O emissions and GWP calculations

Yield-scaled N_2O emissions were calculated as the ratio of the cumulative emissions of N_2O-N at the end of the experimental period to the above-ground N uptake (Nup), and expressed as g N_2O-N kg Nup^{-1} (van Groenigen *et al*., 2010). Global Warming Potential (GWP), expressed in CO_2-equivalents (CO_2-eq), was estimated taking into account cumulative soil emissions of N_2O and CH_4 assuming a 100-year time horizon (Myhre *et al*., 2013) (GHG-GWP). We also considered C sequestration in the first 30 cm of soil and CO_2 emissions from fuel used in farm operations (e.g. tillage, herbicide and fertilizer applications, seeding and harvest) and from manufacturing inputs (operation GHG emission + input GHG emission). The "Δ soil C GWP" component, as an indicator of C soil balance, was calculated taking the difference in SOC stocks between CT (as baseline) and the rest of tillage treatments, dividing it by the number of years since the experiment started and using the CO_2/C molar ratio (Thelen *et al*., 2010). Different soil masses between tillage treatments (as a result of different bulk densities of the tillage treatments) may influence the differences in C sequestration. To avoid this bias, the comparison of C stocks was made on a fixed soil mass basis, as described in Ellert and Bettany (1995). As tillage events were performed shallowly (0-20 cm layer), and differences between tillage systems in SOC contents tend to decrease with depth (Baker *et al*., 2007), we only considered the 0-30 cm soil depth for calculating C sequestration. This is a deeper soil layer than in previous studies (e.g. Mosier *et al*., 2005) in order to include the soil layer altered by moldboard tillage events (Angers and Eriksen-Hamel, 2008). Net GWP was, therefore, calculated as follows (Dendooven *et al*., 2012):

$$\text{Net GWP} = \Delta \text{ soil C GWP} + \text{soil } N_2O \text{ flux} + \text{soil } CH_4 \text{ flux} + \text{operation GHG emission} + \text{input GHG emission}$$

We also included a net GWP calculation without considering input GHG flux (Net Farm GWP). Default values of GHG emissions derived from farm operations and manufacturing inputs have been reported by West and Marland (2002), Lal (2004) and Snyder *et al*. (2009) (Table 1).

2.6. Statistical analysis

Statistical analyses were carried out with Statgraphics Plus 5.1. Analyses of variance of the *split-plot* experiment were performed for almost all variables in the experiment (except climatic ones). Data distribution normality and variance uniformity were assessed by the Shapiro-Wilk test and Levene's statistic, respectively, and log-transformed before analysis when necessary (e.g. N_2O emissions during Period III, total N_2O emissions, NH_4^+-N). Means were separated by Tukey's honest significance test at $P< 0.05$. For non-normally distributed data, the Kruskal–Wallis test was used on non-transformed data to evaluate differences at $P<0.05$. Linear regression analyses were carried out to determine relationships between cumulative gas fluxes and average WFPS, soil temperature, DOC, NH_4^+-N and NO_3^--N. Correlations were performed between these variables for the average/cumulative values (n=18) and also for the dates when both gas and soil samples were taken (n=22), with a 95 % significance level.

3. Results

3.1. Environmental conditions, mineral N, DOC and SOC contents

Total rainfall (Fig. 1a) was 376 mm, of which 297 mm occurred during the crop period. Mean annual temperature (Fig. 1a) was 13.7 °C. Water-filled pore space in the upper soil layer is shown in Figure 1b and c. Values were mostly within the 40-60% range during autumn, winter and spring, decreasing from May until the end of the experiment with values below 20%. The number of days with WFPS above 50% was

45-55, 5-10 and 15-25 for NT, MT and CT treatments, respectively; whereas the mean number of days for the B and V treatments was 23 and 30, respectively.

In V subplots, topsoil NH_4^+-N content was generally below 15 mg NH_4^+-N kg^{-1}, and mean NH_4^+-N content (1.5 mg NH_4^+-N kg^{-1}) was significantly lower (P<0.001) than in B (7.9 mg NH_4^+-N kg^{-1}). In the latter, NH_4^+-N content (Fig. 2a, b) showed a peak during autumn-winter and again in spring, reaching the highest value in B-MT (49.7 mg NH_4^+-N kg $soil^{-1}$) as a result of fertilization events. Soil NO_3^--N content of the topsoil (Fig. 2c, d) increased after fertilization events in B subplots, whereas in V subplots an increment was observed after harvest (12th May 2013). Average NO_3^--N content (considering the whole year) was also significantly higher (P<0.01) in B subplots (11.8 mg NO_3^--N kg^{-1}) than in V subplots (4.8 mg NO_3^--N kg^{-1}). No differences in mineral N content were found between tillage treatments (P>0.05).

No tillage (NT) significantly increased (P<0.05) topsoil DOC content compared with MT and CT on several sampling dates (Fig. 2e, f) in both crops. Considering the whole crop period, mean DOC content for NT was 115.2 mg C kg $soil^{-1}$, which was 46% (P<0.05) and 18% (P>0.05) higher than that obtained for CT (79.0 mg C kg $soil^{-1}$) and MT (97.3 mg C kg $soil^{-1}$), respectively. As for the crop factor, mean topsoil DOC content was 104.6 and 89.7 mg C kg $soil^{-1}$ for V and B, respectively (P<0.05). Soil organic C and C sequestration rates (expressed as Mg CO_2 ha^{-1} yr^{-1}) are shown in Table 2. No tillage significantly increased (P<0.05) SOC concentrations in the 0-7.5 cm layer, and C sequestration in the 0-30 cm layer. Given that no significant differences were observed in SOC contents between both crops after almost 20 years of crop rotation (P>0.05, data not shown), the same SOC and C sequestration values were assumed for both crops in GWP calculations.

3.2. Nitrous oxide, CH_4 and CO_2 emissions

Nitrous oxide (N_2O) fluxes ranged from -0.04 to 0.34 mg N_2O-N m^{-2} d^{-1} in B, and from -0.02 to 0.29 mg N_2O-N m^{-2} d^{-1} in V subplots (Fig. S2a, b). Several emission peaks were observed during the experimental period, and small negative N_2O fluxes were measured on several occasions in all treatments. Increases in N_2O fluxes were observed in spring and autumn in both crops, particularly in B after seeding and dressing fertilization. At the beginning of the crop season before mineral fertilization, emission peaks were observed in all tillage and crop treatments (pulse effect). Winter peaks also occurred in B and V and were generally more pronounced in the latter, especially in the MT and CT treatments. Cumulative N_2O emissions were calculated for four time periods, following Tellez-Rio *et al.* (2015), for V in the same experimental area (Table 3, Fig. 3a, b): Period I- from the beginning of the experiment to the end of autumn, including all tillage events and seeding fertilization in B; Period II- from the beginning of winter to the end of April, including top dressing fertilization in B; Period III- from the end of Period II until cereal harvest (beginning of summer); and Period IV- from harvest to the end of the experimental period. A significant interaction (P<0.05) was found between tillage and crop effects in total N_2O cumulative emissions and cumulative N_2O emissions during Period II (Table 3, Fig. S1). In the CT and MT treatments, V subplots showed the highest N_2O cumulative emissions (P<0.05), whereas in the NT plots B had higher N_2O emissions than V, although differences between the two crops were not significant (P>0.05). Nitrous oxide fluxes correlated with mean DOC content in NT plots (P<0.05, n = 18, r = 0.44), with WFPS in B subplots (P<0.05, n = 18, r = 0.46), and with NH_4^+-N in both crops (P< 0.05, n = 22, r = 0.43).

Methane emissions ranged from -2.0 to 0.4 mg CH_4-C m^{-2} d^{-1} (Fig. S2c, d). Although some positive fluxes were observed, all subplots were net CH_4 sinks during

most of the experimental period. A significant correlation was found between CH_4 cumulative fluxes and mean WFPS values ($P < 0.05$, n = 18, r = 0.56). Respiration rates remained below 1.0 g CO_2-C m^{-2} d^{-1} until spring and then increased, reaching values of 11.7 and 4.9 g CO_2-C m^{-2} d^{-1} for V and B, respectively (Fig. S2e, f). At the end of the crop growing season, CO_2 fluxes decreased again. No significant differences were found in cumulative CH_4 or CO_2 emissions for tillage or crop factors (Table 3). Conversely, the highest spring CO_2 peak (18th April 2013) was significantly greater in V (P<0.05), especially under conservation tillage treatments (MT, NT). Total CO_2 fluxes were significantly correlated with cumulative N_2O emissions (P<0.05, n = 18, r = 0.48) and soil temperature (P<0.05, n = 18, r = 0.45).

3.3. Crop yields, YSNE and GWP

Biomass yields in V subplots were significantly lower (P<0.05) in MT than in CT and NT (Table 1, Supplementary Material). In contrast, tillage did not significantly alter B grain yield or YSNE.

No significant differences in net GHG-GWP were found between tillage or crop treatments (Table 4). Net GWP, Net Farm GWP and Net GWP without considering C sequestration (data not shown) were significantly lower in V than in B, and in the NT treatment compared to MT/CT (P<0.05). The yield-scaled GWP was not affected by tillage (Table 1, Supplementary Material). A significant ´tillage x crop` interaction was found in Net GWP and Net farm GWP (P<0.05). This significant result for interaction was due to a low standard error of the mean, even though the differences between both crops for each tillage system were in the same range (Table 4).

4. Discussion

4.1. Effect of crop and long-term tillage systems on N_2O emissions

Our study suggests that the effect of long-term tillage treatments in rainfed Mediterranean agro-ecosystems on N_2O emissions is highly influenced by the interaction with crop effect (winter cereal or forage legume), affecting the predominance of soil biochemical processes and their final products. We hypothesized that the interaction between tillage and previous crop residues could also play a key role in N_2O emissions. Moreover, the low N_2O fluxes, as a consequence of climatic conditions and management practices, highlight the need to consider other components of the GHG balance and the N emitted/N uptake ratio in order to recommend the best cost-effective mitigation options.

In relation to the effect of tillage on N_2O emissions, NT did not result in lower N_2O emissions in this long-term experiment in any of the two crops, which was contrary to our hypothesis. However, this is in agreement with Rochette (2008), who evaluated 25 field studies that compared NT and CT treatments and concluded that NT promoted higher N_2O fluxes in poorly-aerated soils, whereas in well or medium-aerated soils the effect of NT on N_2O was small, sometimes even decreasing fluxes. Following Rochette's (2008) classification criteria, we indexed our soil as well-aerated (good drainage combined with precipitation below 400 mm during the growing season), and thus expected NT to have a non-significant effect on N_2O emissions (Table 3), in spite of higher SOC (Table 2) and DOC contents (Fig. 3e, f) . Moreover, no differences in bulk density (Table 2) were observed between the NT and CT treatments. Therefore, apparent improvements in soil structure, which have been associated to the adoption of NT (Six *et al.*, 2004; Plaza-Bonilla *et al.*, 2013), were not observed in our study.

An interesting result was the significant (P<0.05) ´tillage x crop` interaction observed (Table 3, Fig. S1). Vetch emitted more N_2O than B in the CT and MT treatments (P<0.05), whereas N_2O emissions were similar for both crops in NT

(P>0.05). We identified Period II (mid-December to the end of April) as the most influential for cumulative emissions and the 'crop x tillage' interaction observed (Table 3, Fig. 3). As NH_4^+ and NO_3^- contents, which were significantly higher in B, are directly involved in nitrification and denitrification processes, respectively, we expected more N_2O to be produced in B treatment. Barton *et al*. (2013) indicated that nitrification rather than denitrification was the main source of N_2O in legume-cereal rotation under semiarid conditions. Although the predominance of nitrification is consistent with the correlation between soil NH_4^+ -N and N_2O fluxes, the results obtained for Period II do not support this hypothesis, because higher NH_4^+ concentrations in B did not result in higher fluxes in these subplots. We suggest that denitrification could be the main process producing the differences observed in N_2O fluxes during Period II, when the highest WFPS values were observed. Some abiotic factors favoring denitrification (i.e. soil DOC contents and the number of days with WFPS > 50%) were higher in V than in B. These could have offset other factors that may have favoured greater N_2O losses in B subplots, such as higher NH_4^+ and NO_3^- contents. The balance between N_2O production and consumption by denitrifiers could explain the significant ´tillage x crop` interaction observed (Table 3). In B, the tendency for larger emissions in B-NT compared with B-CT and B-MT (Fig. S1, Table 3) could be explained by conditions conducive to denitrification in non-tilled soils (i.e. higher WFPS and DOC content) (Fig. 1c, 2e, f). In V, the numerically (but not statistically) lower emissions observed in V–NT could be due to a greater potential to denitrify through to N_2 rather than N_2O under favorable denitrification conditions (DOC content) associated with both tillage (NT) and crop (V) factors (Saggar *et al.*, 2013). The low NO_3^- -N content (< 5 mg NO_3^--N kg^{-1}) observed in V could lead to the use of N_2O as an electron acceptor instead of more oxidized forms (i.e. NO_3^-), thus decreasing the N_2O/N_2 ratio. Hence, the higher NO_3^--N content in B

subplots could explain the increase in N_2O fluxes in the tillage treatment (NT) with most propitious conditions (higher DOC, WFPS) for denitrification (Fig. S1). This is supported by the DOC/NO_3^- ratio, which Abalos *et al*. (2013) considered to be a good indicator of N_2O fluxes, highlighting the increased consumption of N_2O when DOC/NO_3^->2. In our experiment, the higher ratio in V-NT (mean 40.3) than in B-NT (mean 8.2) (data not shown) suggested that N_2O consumption was more favored in V.

The effect of tillage and residue type on mineralization rates could also partially explain the ´tillage x crop` interaction. Higher denitrification losses (which may have had a large influence on cumulative N_2O emissions in this experiment, as suggested above) and slower mineralization rates were expected in V. This is because these subplots were amended with a high C:N wheat residue (mean C content: 42.2 %, mean N content: 0.40 %), which is difficult to break down by soil microbiota (Heal *et al*., 1997) and provides a C source for denitrifiers. In fact, Abalos *et al*. (2013) observed a peak of N_2O in spring (6 months after the incorporation of maize stover) due to a synergic effect between C released from residue mineralization and N applied at dressing. On the other hand, the V residue, which is much less recalcitrant because of its lower C:N ratio (mean C content: 41.0 %, mean N content: 3.71 %), was applied in B subplots. Tillage could also have had an important effect on mineralization of previous residues in our experiment. In the case of wheat residue (V subplots) the treatments that incorporated residue in the soil (MT, CT) had faster mineralization rates (and higher N_2O fluxes) than NT treatments, where residues were left on the soil surface (Almaraz *et al*., 2009). In the case of V residues (B subplots), the spring N_2O peak associated with a slower mineralization rate could be expected in NT. Therefore, crop residues could have played a key role in N_2O emissions, and that should be taken into account in the comparison between V and B.

As expected, cumulative N_2O emissions (167.7 to 288.0 g N_2O-N ha^{-1} yr^{-1}) (Table 3) were in the lowest ranges reported for rainfed legumes and cereals (Jensen *et al*., 2012; Kim *et al*., 2013). These low emissions were due to low winter temperatures and WFPS values (<50% from 310 to 360 days depending on tillage treatment), which are the most limiting factors for winter rainfed crops (Aguilera *et al*., 2013). Moreover, the low or zero fertilizer amendment and soil conditions (e.g. low fertility and SOC contents, and good aeration) did not favour high N losses (MacKenzie *et al*., 1998; Cui *et al*., 2012).

4.2. Methane emissions

All crop and tillage treatments were net sinks of CH_4 as usually reported in arable soils (Snyder *et al*., 2009), and no significant differences were found between tillage or crop treatments (Table 3, $P > 0.05$). These results on the effect of tillage were consistent with those of other studies under semiarid conditions (Tellez-Rio *et al*. 2015; Plaza-Bonilla *et al*., 2014a). The absence of significant effects could be due to the low soil moisture content maintained throughout almost all the experimental period and the non-significant improvement of soil porosity in the NT system (Table 2), which could have been caused by the high sand content of the soil (see section 2.1).

Crop fertilization did not produce significant differences on CH_4 emissions. Soil NH_4^+ is known to inhibit CH_4 consumption by methanotrophs due to competitive inhibition of the enzyme responsible for CH_4 oxidation (CH_4 monooxygenase) with the NH_3 monooxygenase (Dunfield and Knowles, 1995; Le Mer and Roger, 2001). Nevertheless, in our experiment CH_4 sinks were similar in V (non-fertilized) and B (fertilized). The low amount of NH_4^+ applied as fertilizer to B (28 kg NH_4^+-N ha^{-1} at

dressing), which increased soil NH_4^+-N content only during 50-60 days after application, may not be enough to produce significant differences.

4.3. Yield-scaled N_2O emissions and GWP

The N_2O efficiency of a cropping system, in a context of increasing food demand, should be expressed in terms of YSNE (van Groenigen *et al*., 2010). In addition, crop yields should be also assessed independently, aiming to find strategies potentially acceptable by farmers (minimizing the YSNE without significant yield decrease) (Sanz-Cobena *et al*., 2014b). Considering all potential GHG sinks and sources is also mandatory when implementing management practices with potential side-effects on C sequestration, input demand and fuel consumption (Robertson *et al*., 2000).

No differences were observed in grain or biomass yields between the NT and CT treatments (Table 1, Supplementary Material), probably because 2013 was an average year in terms of rainfall (Fig. 1a), especially during the most critical period of the crop growing cycle (flowering period at spring), which could have masked differences in soil water content and water use efficiency due to tillage. In the meta-analysis of van Kessel *et al*. (2013), no significant effect of NT on crop yield was found under conditions similar to those of our experiment (dry climate and > 10 years since NT/CT implementation). Our results were also supported by the meta-analysis of Pittelkow et al. (2015) for the climatic and management conditions of our study (dry climate, rainfed conditions, 0 or low N rate and crop rotation with retention of residues). By contrast, significantly lower yield values were obtained in V-MT than in V-NT/V-CT (Table 1, Supplementary Material), which could be a result of higher weed population of these plots (Armengot *et al*., 2015).

Yield-scaled N_2O emissions were 2.4 times higher in B than in V ($P < 0.01$) (Table 3), which is the same proportion obtained by Malhi and Lemke (2007) in a comparison of barley and pea crops. However, the comparison between a fertilized cereal and a non-fertilized N fixing crop should be taken with caution as it is estimated that 78% of biomass N in forage legumes comes from N_2 fixation (Anglade et al., 2015), thus affecting the residual N in soils and potential N losses. Yield-scaled N_2O emission values were considerably low compared to those reported in the meta-analysis of van Groenigen *et al*. (2010) for low (< 100 kg ha^{-1}) or even zero N-input systems, but in agreement with those reported by Tellez-Rio *et al*. (2015) for V under similar conditions. When this index was expressed as kg of CO_2-eq emitted per kg of grain produced, values (0.01-0.02) were also consistent with those obtained by Plaza-Bonilla *et al.* (2014b) in a rainfed Mediterranean barley field, and were much lower than the mean value obtained by Skinner *et al*. (2014) for arable non-organic fields (0.15 kg CO_2-eq. kg DM^{-1}). Although this campaign could be considered as "representative" with regard to rainfall and temperature, YSNE should also be assessed under more unusual conditions (e.g. very dry and very wet campaigns, that could affect N_2O fluxes and the effect of tillage on crop yields) in order to determine the range of YSNE values in this agro-ecosystem and for each treatment. Unlike van Kessel *et al*. (2013), who described a significant decrease in N_2O emissions per kg of yield in dry climates and long-term experiments (≥ 10 years) under NT systems, we did not find differences in YSNE between tillage treatments. This could be due to the small differences in yield and low total N_2O emissions.

Net GWP calculations identified NT and V as the most sustainable alternatives among the tillage and crop factors, respectively. The comparison of Net GWP components showed that N_2O fluxes (<120 kg CO_2-eq ha^{-1}) had a lower influence than

C sequestration, farm inputs or operations (Fig. 4). A similar result was found by Aguilera *et al*. (2014) in a Life Cycle Assessment of Mediterranean cropping systems. However, contrasting results have been found in other crop systems where N_2O fluxes were above 200 kg CO_2-eq ha^{-1} (Adviento-Borbe *et al*., 2007; Dendooven *et al*., 2012).

In relation to the tillage treatments, NT had the highest C sequestration rate, in agreement with results from previous studies (Franzluebbers *et al*., 1998; Morris *et al*., 2004), and the lowest Net GWP value (-1498.7 kg CO_2-eq ha^{-1} yr^{-1}, Table 4), as shown by the greater mean annual C sequestration in NT compared to CT (Table 2). However, this mean value (´Δ soil C GWP` component) is dependent on factors such as: 1) the soil depth used for calculation, which may have affected SOC distribution in NT *versus* CT systems (Baker *et al*. 2007); and 2) the assumption of a linear C sequestration pattern in time, when the annual rate actually tends to decrease in the long-term (Álvaro-Fuentes *et al*., 2014). In this sense, values reported by Martin-Lammerding *et al.* (2011) corresponding to 2007 (Table 2), revealed that bulk density and C stocks are very dependent on the number of years considered since the beginning of the experiment. Another consideration is that this component measured the relative increase in C sequestration (using CT as a baseline), so it might only be valid for comparing treatments. With the information from 2007, C sequestration would have differed much less between tillage treatments, highlighting the bias associated to this index and the need to strongly consider site-specific GHG emissions data.

Farm operations and inputs, which were considered for Net GWP calculation, were also dependent on tillage. No tillage plots had the lowest ‘operation + input GHG emission’ value (508.1 kg CO_2-eq ha^{-1} yr^{-1}), mainly due to a reduction in the number of labor operations. Therefore, other farm operations and inputs, such as herbicide application and manufacturing, which were more frequent in NT than in tilled plots, had

a lower impact on Net GWP than the fuel demand for tillage operations. In this sense, cumulative N_2O emissions in NT plots would have to reach almost 405 g N_2O-N ha^{-1} yr^{-1} to obtain similar values to the CO_2-eq from tillage and other farm operations in CT. This is twice the value of those reported in this experiment, but in the range of other studies in Mediterranean areas (Aguilera *et al*., 2013). If the effect of C sequestration is also considered, NT would have to emit 8.8 kg N_2O-N ha^{-1} yr^{-1}, which is even greater than the emission rate of European grasslands sites (Rees *et al*., 2013). Regardless of the uncertainties associated with the calculation of C sequestration, N_2O losses were smaller than CO_2-eq from farm inputs and operations (Fig. 4). Therefore, the adoption of NT should be recommended for reducing the GWP in rainfed semi-arid agro-ecosystems.

In this long-term experiment, the crop factor affected Net GWP components such as N_2O emissions (higher in V than in B) and farm operations and inputs (higher in B than in V) (Table 4, Fig. 4). Carbon dioxide fluxes derived from the higher fertilizer and herbicide demand in B explained the higher Net-GWP in this treatment. Thus, N_2O emissions in V subplots would have to be 10 times higher (2.4 kg N_2O-N ha^{-1} yr^{-1}) than those reported to offset CO_2-eq from farm operations and manufacturing inputs associated with B crops in this experimental area. Our results agree with those of Mosier *et al*. (2005) and Adviento-Borbe *et al*. (2007) under different climatic conditions, suggesting that crop rotation systems including legumes are advisable strategies to reduce Net GWP as opposed to continuous cropping of winter cereals, and an opportunity to lower farm costs as a result of lower input demands (Kassam *et al*. 2012; Jensen *et al*., 2012). These results should be confirmed with further long-term experiments assessing the whole rainfed crop rotation (fallow-cereal-legume-cereal),

compared with cereal monoculture and cereal-based rotations (cereal-fallow) in semi-arid agro-ecosystems.

5. Conclusions

Low cumulative N_2O fluxes (which were influenced by 'tillage x crop' interactions) and yield-scaled N_2O losses constituted an important advantage of rainfed cereal/legume agro-ecosystems. The analysis of other GHG sources and potential sinks through Net GWP calculations indicate that NT was the most useful strategy to reduce CO_2-equivalent fluxes, mainly as a result of C sequestration and lower fuel consumption. Furthermore, the non-fertilized legume crop is also recommended for reducing Net GWP (in spite of higher N_2O emissions under CT and MT), mainly through the reduction of inputs (N fertilizers and herbicides). Therefore, the use of Conservation Agriculture practices such as NT and crop rotation including legumes, as opposed to continuous cropping of winter cereals, could be considered as a good strategy in semiarid agro-ecosystems for decreasing Net GWP without affecting crop yield.

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Figure captions

Fig. 1a Weekly mean air and soil temperatures (°C) and rainfall (mm) and soil WFPS (%) in the three tillage treatments (no tillage, NT, minimum tillage, MT, and conventional tillage, CT) in **b** vetch (V) and **c** barley (B) during the experimental period.

Fig. 2a, b NH_4^+-N; **c, d** NO_3^- -N; and **e, f** DOC concentrations in the 0–15 cm soil layer during the experimental period for the three tillage treatments (no tillage, NT, minimum tillage, MT, and conventional tillage, CT). Data are provided separately for V (left) and B (right) treatments. Vertical lines indicate standard errors.

Fig. 3 Cumulative N_2O emissions for no tillage (NT), minimum tillage (MT) and conventional tillage (CT) treatments during the four measurement periods (I, II, III and IV) in **a** vetch (V) **b** barley (B). Vertical lines indicate standard errors.

Fig. 4 Contribution of each GWP component (kg CO_2-eq $ha^{-1}yr^{-1}$) to mean Net GWP values in the different tillage (no tillage, NT, minimum tillage, MT, and conventional tillage, CT) and crop (vetch, V, and barley, B) treatments. The ´GHG-GWP` component indicates the sum of CO_2 equivalents from N_2O and CH_4 emissions, considering a 100-year horizon.

Fig. S1 Significant ´tillage x crop´ interaction for N_2O cumulative emissions. The (*) indicates significant differences within each tillage (no tillage, NT, minimum tillage, MT, and conventional tillage, CT) between the two crops (vetch, V, and barley, B) at $P<0.05$. Vertical bars indicate the standard error of the mean.

Table 1

Annual CO_2-equivalent emissions related to agronomic practices (operations and inputs) in the different tillage (no tillage, NT, minimum tillage, MT, and conventional tillage, CT) and crop (vetch, V, and barley, B) treatments.

Source	CO_2 equivalents	Observations	Reference
Operations			
Conventional tillage (moldboard plow)	98.1 kg CO_2 ha^{-1} $tillage^{-1}$	One moldboard operation in CT plots	West and Marland, 2002
Minimum tillage	32 kg CO_2 ha^{-1} $tillage^{-1}$	Two and one tillage operations in MT and CT plots, respectively	West and Marland, 2002
Herbicide application	5.1 kg CO_2 ha^{-1} $spraying^{-1}$	Two applications in B-NT plots and one application in B-MT and B-CT plots	Lal, 2004
Seeding fertilizer application	45.3 kg CO_2 ha^{-1} $application^{-1}$	Dressing fertilization was spreading homogenously by hand.	West and Marland, 2002
Sowing	17.3 and 13.9 kg CO_2 ha^{-1} $sowing^{-1}$	For NT and MT/CT, respectively	Lal, 2004
Harvesting	60.39 kg CO_2 ha^{-1} $harvesting^{-1}$		West and Marland, 2002
Inputs			
Herbicides	17.2 kg CO_2 kg^{-1}	3.6 L ha^{-1} in B-NT and 1.6 L ha^{-1} in B-MT and B-CT. Density =1 kg L^{-1} was assumed	West and Marland, 2002
N seeding	3.1 kg CO_2 kg^{-1}	16 kg N ha^{-1} applied in B	West and Marland, 2002
P seeding	0.6 kg CO_2 kg^{-1}	48 kg P_2O_5 ha^{-1} applied in B	West and Marland, 2002
K seeding	0.4 kg CO_2 kg^{-1}	16 kg K_2O ha^{-1} applied in B	West and Marland, 2002
N dressing	9.7 kg CO_2 kg N-AN^{-1}*	54 kg N ha^{-1} applied as AN	Snyder et al., 2009
Seed	0.11 kg CO_2 kg^{-1}	210 and 120 kg ha^{-1} in B and V, respectively. The same CO_2 emissions were assumed for both crops	West and Marland, 2002

* AN means Ammonium Nitrate

Table 2

Bulk density (Mg m^{-3}), SOC content (g C kg^{-1}) in the 0-7.5, 7.5-15 and 15-30 cm layers, total SOC content (Mg C ha^{-1}) and C sequestration (C seq, Mg CO_2 ha^{-1} yr^{-1}) in the 0-30 cm depth of the different tillage treatments (no tillage, NT, minimum tillage, MT, and conventional tillage, CT).

		Bulk density (Mg m^{-3})		SOC (g kg^{-1})			Total SOC (Mg ha^{-1})	C seq (Mg CO_2 ha^{-1} yr^{-1})
Depth (cm)		0-7.5	7.5-30	0-7.5	7.5-15	15-30	0-30	
Year		2012 (2007)		2012			2012 (2007)	
Tillage	NT	1.39 (1.52)	1.55 (1.58)	11.0 b	6.5	7.3	38.3 b (33.2)	7.8 b (8.7)
	MT	1.22 (1.24)	1.43 (1.36)	7.8 a	7.2	6.6	31.9 a (32.7)	6.5 a (8.6)
	CT	1.30 (1.38)	1.52 (1.49)	6.1 a	6.3	6.3	28.3 a (31.9)	5.8 a (8.4)
S.E.		0.10		0.5	0.9	1.0	2.5	0.5

Values in brackets have been obtained from Martín-Lammerding *et al*. (2011) and correspond to 2007. C sequestration rate was calculated dividing by the number of years since the experiment started (18) and considering the CO_2/C molar ratio. Different letters within columns indicate significant differences by applying the Tukey's honest significance test at $P < 0.05$. Standard Error (S.E.) is given for each effect.

Table 3

Cumulative N_2O-N emissions over the different periods of field experiment, total cumulative N_2O-N, CH_4-C and CO_2-C fluxes and yield-scaled N_2O emissions (YSNE) in the different tillage (no tillage, NT, minimum tillage, MT, and conventional tillage, CT) and crop (vetch, V, and barley, B) treatments.

Effect	N_2O cumulative emission (g N_2O-N ha^{-1} yr^{-1})				Total N_2O-N (g N_2O-N ha^{-1} yr^{-1})	CH_4 cumulative emission (g CH_4-C ha^{-1} yr^{-1})	CO_2 cumulative emission (Mg CO_2-C ha^{-1} yr^{-1})	YSNE (g N_2O-N kg N up^{-1})
	I period	II period	III period	IV period				
Tillage	*P* = 0.189	*P* = 0.137	*P* = 0.275	*P* = 0.497	*P* = 0.931	*P* = 0.193	*P* = 0.095	*P* = 0.133
NT	57.0	84.8	46.0	11.9	199.7	-580.8	2.9	1.6
MT	51.8	103.2	57.9	1.0	213.9	-890.9	3.5	2.0
CT	88.7	93.8	20.0	6.0	208.6	-760.9	2.9	1.4
S.E.	12.4	5.0	14.4	5.9	30.6	90.8	0.2	0.2
Crop	*P* = 0.527	*P* = 0.002	*P* = 0.811	*P* = 0.767	*P* = 0.021	*P* = 0.501	*P* = 0.178	*P* = 0.005
V	62.8	125.3 b	43.2	11.5	235.9 b	-710.4	3.3	1.0 a
B	68.9	62.6 a	39.4	8.0	178.9 a	-790.0	2.9	2.3 b
S.E.	6.3	8.5	10.6	7.8	15.0	70.6	0.2	0.2
Tillage x crop	*P* = 0.480	*P* = 0.040	*P* = 0.821	*P* = 0.377	*P* = 0.049	*P* = 0.386	*P* = 0.222	*P* = 0.395
V-NT	50.6	88.6 Aa	42.0	10.35	191.1 Aa	-625.2	2.7	0.6
B-NT	64.0	80.9 Aa	50.0	13.4	208.3 Aa	-550.0	3.0	2.6
V-MT	56.9	155.6 Bb	65.6	9.9	288.0 Ba	-750.0	3.8	1.5
B-MT	46.6	50.8 Aa	50.1	13.1	160.7 Aa	-1048.3	2.2	2.4
V-CT	81.5	131.5 Bab	21.9	14.4	249.3 Ba	-765.5	3.3	0.8
B-CT	96.0	56.1 Aa	18.1	-2.5	167.7 Aa	-772.3	2.4	1.9
S.E. *	15.5	20.8	26.0	19.2	34.8	185.3	1.5	0.5
S.E. **		16.3			46.3			

Different letters within columns indicate significant differences by applying the Tukey's honest significance test at $P<0.05$. Standard Error (S.E.) is given for each effect. * is the standard error of the mean when comparing crops within each tillage treatment. In the case of significant interactions, the standard error of

the mean when comparing tillage treatments within a crop (**) is also given. Different capital letters in the interaction indicate significant differences between crops within a tillage treatment, whereas different lowercase letters indicate significant differences between tillage treatments within a crop, by applying the Tukey's honest significance test at $P<0.05$.

Table 4

Estimated Global Warming Potential (GWP, kg CO_2 eq ha $^{-1}$ yr^{-1}) for the different tillage (no tillage, NT, minimum tillage, MT, and conventional tillage, CT) and crop (vetch, V, and barley, B) treatments.

	Global Warming Potential (kg CO_2 eq ha $^{-1}$ yr^{-1})					
Effect	GHG-GWP [a]	C seq [b]	Operations	Inputs	Net GWP [c]	Net farm GWP [d]
Tillage	*P* = 0.431	*P* = 0.001			*P* = 0.012	*P* = 0.000
NT	27.7	-2034.4 a	105.4	402.7	-1498.7 a	-1183.3 a
MT	26.1	-220.0 b	163.4	385.4	335.1 b	-11.3 b
CT	35.5	0 b	229.6	385.4	650.5 b	273.3 b
S.E.	4.9	708.4			713.4	713.4
Crop	*P* = 0.225				*P* = 0.000	*P* = 0.003
V	31.9	-751.5	140.1	48.4	-531.1 a	-556.1 a
B	27.6	-751.5	192.2	733.9	202.3 b	-524.9 b
S.E.	2.3				2.3	2.3
Tillage x crop	*P* = 0.088				*P* = 0.001	*P* = 0.041
V-NT	24.8				-1883.5 Aa	-1931.90 Aa
B-NT	30.5				-1113.8 Ba	-1870.75 Ba
V-MT	33.9				0.55 Aa	-47.86 Aa
B-MT	18.4				709.6 Ba	-12.90 Ba
V-CT	37.0				289.8 Aa	241.39 Aa
B-CT	34.0				1011.3 Ba	288.77 Ba
S.E.*	5.5				5.5	5.5
S.E.**					1008.8	1008.8

Different letters within columns indicate significant differences by applying the Tukey's honest significance test at $P < 0.05$. Standard Error (S.E.) is given for each effect. * is the standard error of the mean when comparing crops within each tillage treatment. In the case of significant interactions, the standard error of the mean when comparing tillage treatments within a crop (**) is also given. Different capital letters in the interaction indicate significant differences between crops within a tillage treatment, whereas different lowercase letters indicate significant differences between tillage treatments within a crop, by applying the Tukey's honest significance test at $P<0.05$.

[a] Sum of CO_2 equivalents from N_2O and CH_4 emissions, considering a 100-year horizon.

[b] CO_2 equivalents from C sequestration, calculated taking the difference in SOC stocks between CT (as baseline) and the rest of tillage treatments, dividing it by the number of years since the experiment started (18) and considering the CO_2/C molar ratio.

[c] Sum of CO_2 equivalents from N_2O and CH_4 emissions, C sequestration (C seq), operations and inputs.

[d] Difference of Net GWP and CO_2 equivalents from inputs production and post-production.

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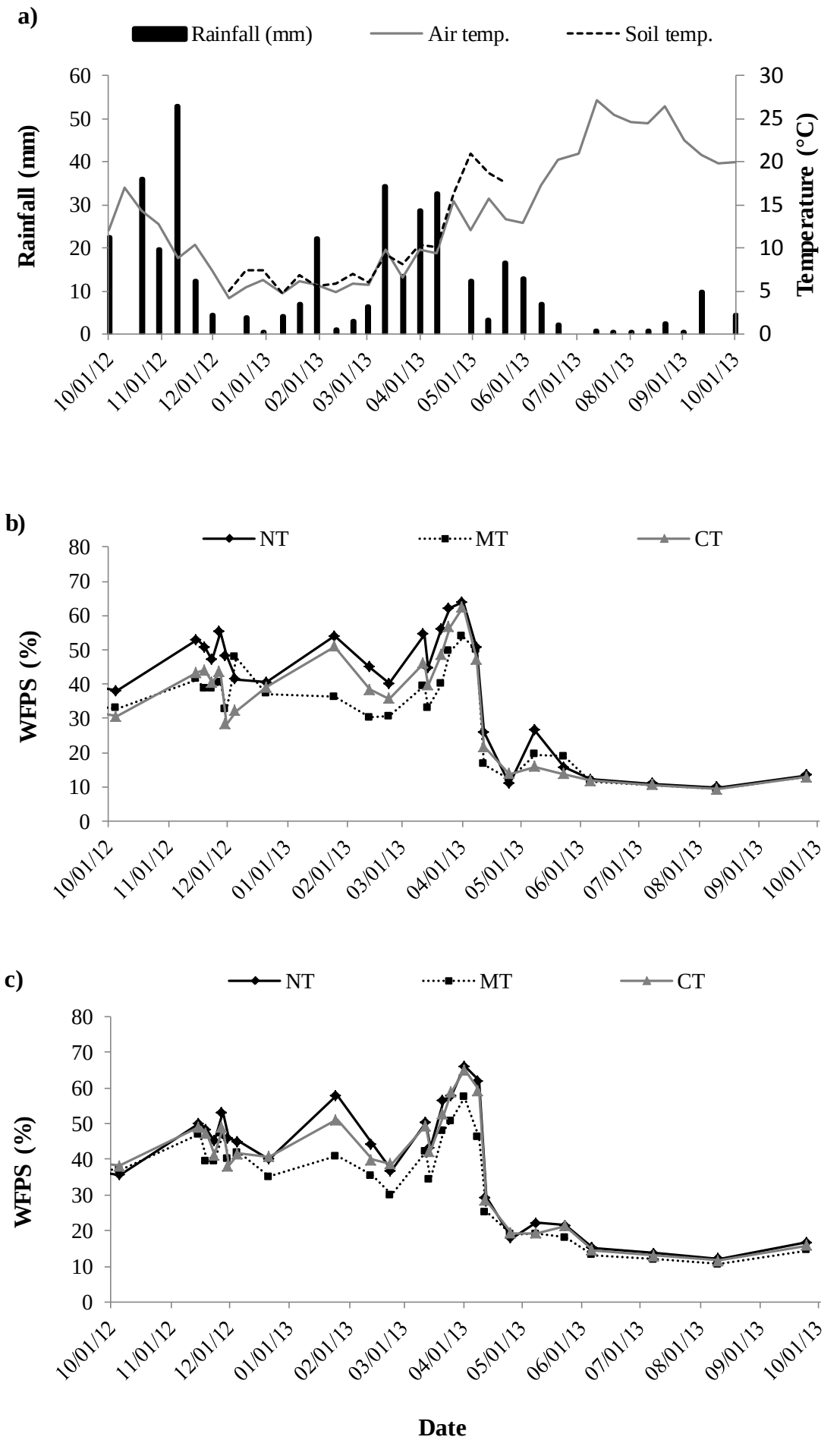

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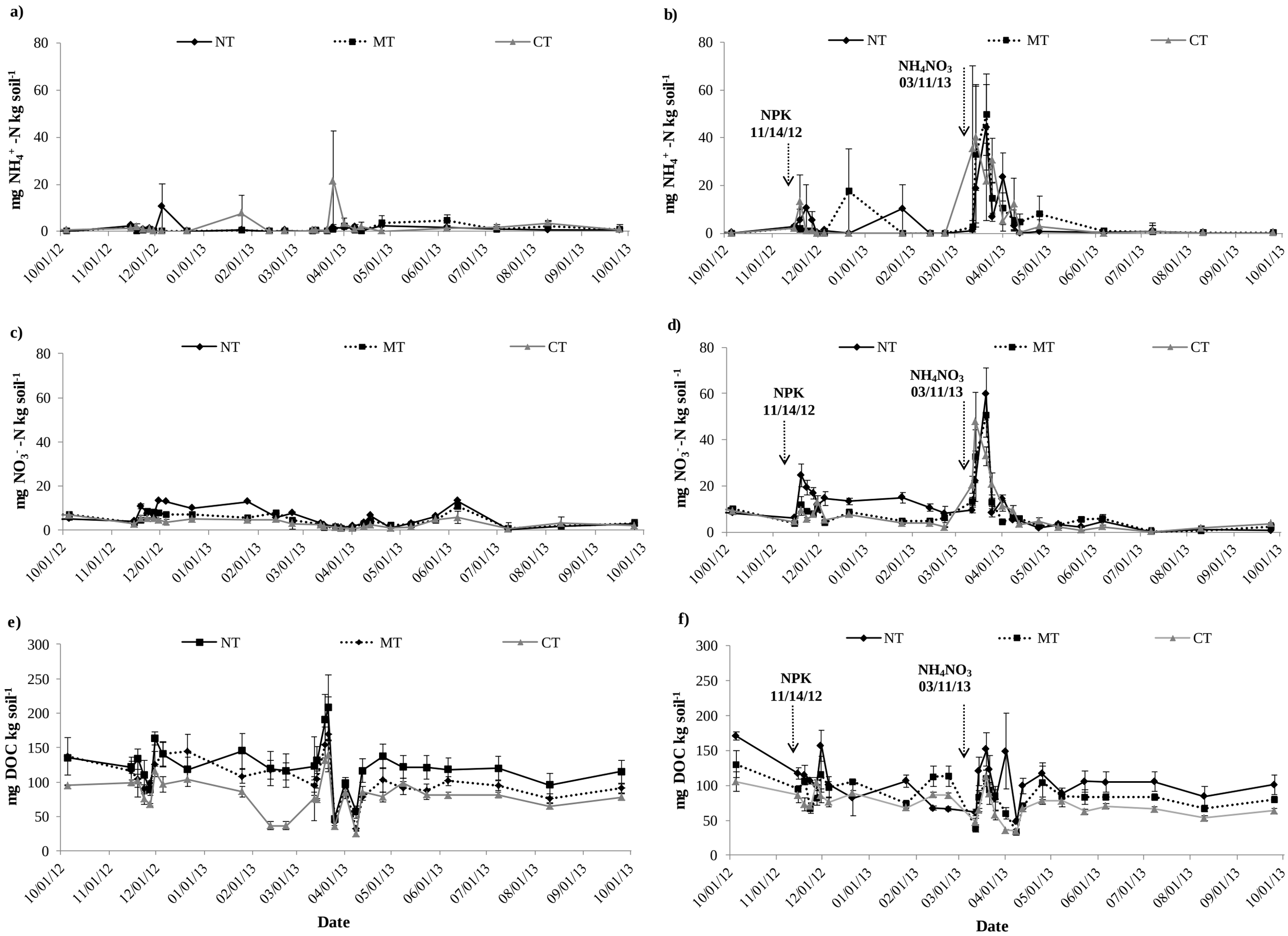

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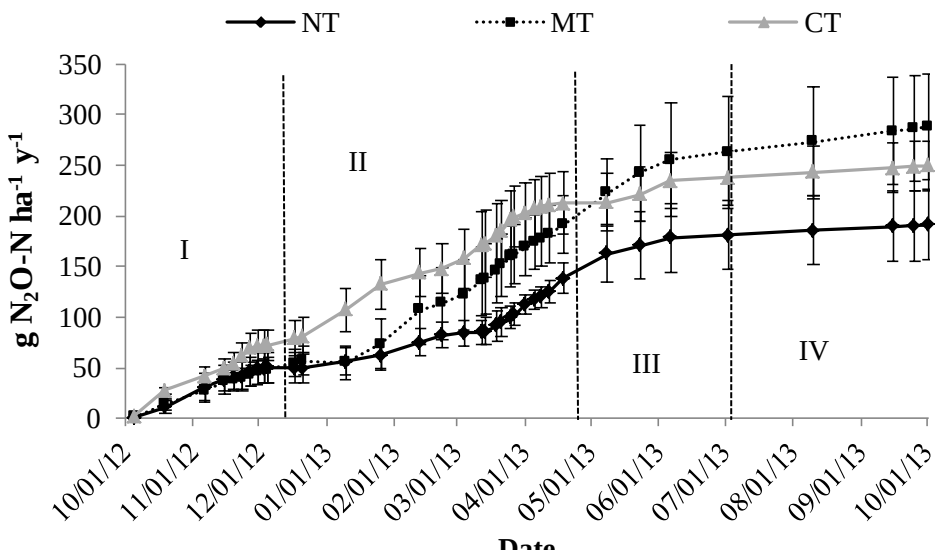

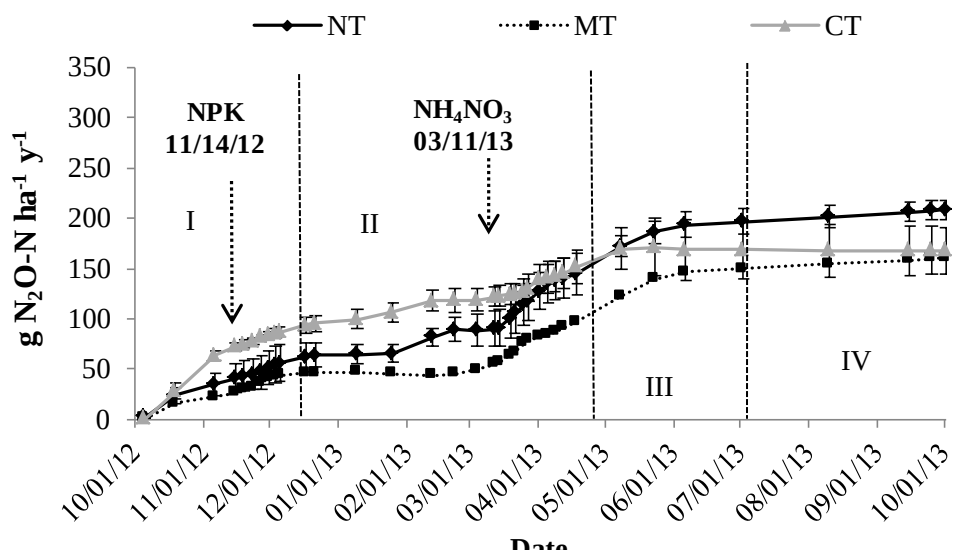

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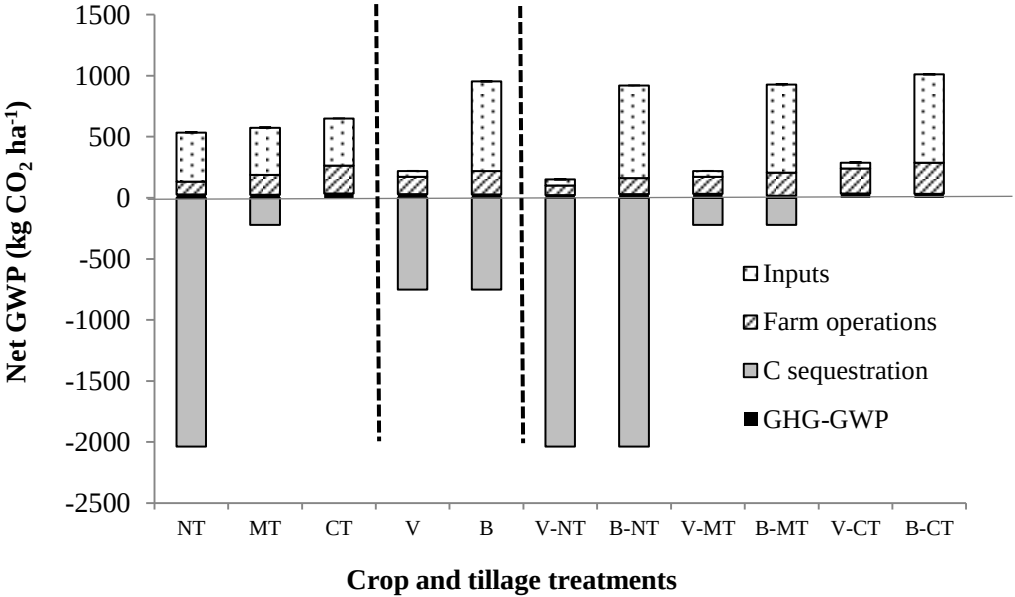

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